

Anisotropic J/Ψ suppression in nuclear collisions

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The nuclear overlap zone in non-central relativistic heavy ion collisions is azimuthally very asymmetric. By varying the angle between the axes of deformation and the transverse direction of the pair momenta, the suppression of J/Ψ and Ψ' will oscillate in a characteristic way. Whereas the average suppression is mostly sensitive to the early and high density stages of the collision, the amplitude is more sensitive to the late stages. This effect provides additional information on the J/Ψ suppression mechanisms such as direct absorption on participating nucleons, comover absorption or formation of a quark-gluon plasma. The behavior of the average J/Ψ suppression and its amplitude with centrality of the collisions is discussed for SPS, RHIC and LHC energies with and without a phase transition.

I. INTRODUCTION

The observed suppression of J/Ψ and Ψ' in nuclear collisions at SPS energies [1] has created much interest, in particular whether the “anomalous” suppression in central $Pb + Pb$ collisions can be attributed to the formation of a quark-gluon plasma [2,3]. It has been found (see, e.g., [4]) that in p+A reactions the suppression can be understood as Glauber absorption of Charmonium states $\psi = J/\Psi, \Psi', \chi$, on participant nucleons with $\sigma_{\Psi N} = 7.3$ mb. At SPS energies also the J/Ψ suppression in $S + A$ and peripheral $Pb + Pb$ collisions can be explained reasonably well but the model fails for central Pb+Pb reactions. Additional break up on *comovers* can, however, also account for the observed strong suppression [5] as is supported by microscopic approaches [6,7]. Understanding the early state dynamics in ultrarelativistic heavy ion reactions is one of the major tasks in view of the upcoming experiments at RHIC and LHC.

We will here suggest a new method to explore the J/Ψ suppression mechanism which exploits the anisotropy of the overlap zone in semi-central collisions. We will demonstrate how the azimuthal distributions of charmonia depends on the initial asymmetry and can give additional information on formation/dissociation processes, in particular when and where they occur. We find that the azimuthal asymmetry is $\sim 5\text{-}10\%$ for semi-central Pb+Pb collisions at SPS energies and more than doubles at RHIC and LHC energies. This is to be compared to the present experimental uncertainty of 1-2% in the J/Ψ minimum bias data of NA50 [1]. It is, however, less than the typical elliptic flow $2v_2 \simeq 20\%$ at SPS [9]. Measuring the reaction plane in coincidence with J/Ψ 's is therefore a promising method which provides new insight in J/Ψ absorption mechanisms and possible phase transitions.

The two important mechanisms for J/Ψ suppression, comover and Glauber absorption, are discussed in Sec. II and III respectively with emphasis on the azimuthal asymmetries. Result for SPS, RHIC and LHC energies are presented in Sec. IV, effects of a phase transition is

discussed in Sec. V, and finally a summary is given.

II. ASYMMETRIES IN COMOVER ABSORPTION

We describe the evolution of the charmonium distribution by the Boltzmann equation

$$\left(\frac{\partial}{\partial t} + \mathbf{v}_p \cdot \nabla \right) n_\psi = - \int \frac{d^3 p_c}{(2\pi)^3} v_{\psi c} \sigma_{\psi c} n_\psi n_c, \quad (1)$$

where $n_i(r_i, p_i, t)$ are the particle distribution functions, $\sigma_{\psi c}$ is the comover absorption cross section for scatterings of charmonia ψ with a comover c and $v_{\psi c}$ their relative velocities.

Let us first consider peripheral nuclear collisions where the overlap zone and the produced particle densities are small. Collisions are then rare and their effects can be calculated to first order with the free streaming distribution functions in the collision term of the Boltzmann equation Assuming Bjorken scaling along the beam or z-axis, $v_z = z/t$. The free streaming distribution can at later times be approximated by [10,11]

$$n(x, p) \simeq \frac{(2\pi)^3}{\tau m_\perp} \delta(y - \eta) \frac{dN}{dy d^2 p_\perp} S_\perp(\mathbf{r} - \mathbf{v}(\tau - \tau_0)). \quad (2)$$

Here, $\mathbf{r} = (x, y)$ is the transverse radius and $\mathbf{v} = (v_x, v_y)$ the transverse velocity of the scatterers or comovers. As usual, $\eta = (1/2) \log((t+z)/(t-z))$ is the space-time rapidity and $\tau = \sqrt{t^2 - z^2}$ is the invariant time. τ_0 is the formation time for comovers.

The transverse particle density distribution, $S_\perp(x, y)$, is for convenience approximated by simple gaussians

$$S_\perp(x, y) = \frac{1}{2\pi R_x R_y} \exp \left(-\frac{x^2}{2R_x^2} - \frac{y^2}{2R_y^2} \right). \quad (3)$$

The rms radii of the overlap zones R_x and R_y at collision are determined from nuclear thickness functions [11].

The x-direction is chosen along the impact parameter \mathbf{b} and (x, z) constitutes the *reaction plane* with y perpendicular to the reaction plane. Replacing the gaussian transverse particle distribution by a constant density inside an ellipse with axes $R_{x,y}$ in Eq. (3) does not change results by much. The only relevant scale is $v_{x,y}\tau/R_{x,y}$ which contains the direction of \mathbf{p}_\perp and the transverse anisotropy.

The integration over transverse coordinates and rapidity is straight forward (see [11] for details). The scatterer momenta can also be summed over and in the following we will by $\langle \dots \rangle$ indicate averaging over scatterer momenta p_c . Only an integral over proper time is left. With $N_i = dN_i/dp_\perp dy$ we obtain for the comover absorption

$$\frac{dN_\psi}{d\tau} = -N_\psi \tilde{\sigma}_\psi \frac{1}{\tau} \exp \left[-\left(\frac{\tau}{\tau_0} - 1 \right)^2 \xi^2 \right], \quad (4)$$

where we have defined the dimensionless quantity

$$\xi \equiv (\tau_0/2) \sqrt{\langle v_{x,\psi c}^2 / R_x^2 + v_{y,\psi c}^2 / R_y^2 \rangle} \quad (5)$$

and the cross section times a transverse particle density, i.e. an effective “opacity”, as

$$\tilde{\sigma}_\psi \equiv \sum_c \frac{dN_c}{dy} \frac{\langle v_{\psi c} \sigma_{\psi c} \rangle}{4\pi R_x R_y}, \quad (6)$$

In the participant or “wounded nucleon” model, which seems to describe the gross properties of relativistic nuclear collisions reasonably, both the rapidity density dN/dy and the transverse area $R_x R_y$ scales approximately with E_T , except for very peripheral collisions (see, e.g., [6,11]). Therefore the opacity $\tilde{\sigma}$ of Eq. (6) is approximately *constant* for central and semi-central collisions but decreases for very peripheral collisions. The almost constant opacity is different from the comover model of [5] which assumes densities to scale linearly with transverse energy.

The dependence on the azimuthal angle ϕ between the reaction plane and the charmonium transverse velocity $(v_x, v_y)_\psi = v_\psi (\cos \phi, \sin \phi)$, (see Fig. 1) is coupled to the source deformation

$$\delta \equiv \frac{R_y^2 - R_x^2}{R_y^2 + R_x^2}. \quad (7)$$

Defining the mean radius $R^2 \equiv (R_x^2 + R_y^2)/2$, we obtain

$$\xi^2 \simeq \frac{\langle v_{\psi c}^2 \rangle \tau_0^2}{4R^2} \left(1 + \delta \frac{v_\psi^2}{\langle v_{\psi c}^2 \rangle} \cos(2\phi) \right). \quad (8)$$

Here, we have expanded assuming $\delta(v_\psi^2/\langle v_{\psi c}^2 \rangle) \ll 1$, which is valid for charmonia with $p_\perp \simeq 1$ GeV.

The deformation can be approximated from the full transverse extent of the initial overlap of two nuclei with radius R_A colliding with impact parameter b (see Fig. 1). They are simply: $R_x = R_A - b/2$ and $R_y = \sqrt{R_A^2 - b^2/4}$,

and the corresponding deformation is $\delta = b/2R_A$. Taking the rms radii of the nuclear overlap zone weighted with longitudinal thicknesses gives almost the same and may be related to the elliptic flow and HBT radii [11].

For peripheral collisions, where the comover absorption is small, we obtain by integrating Eq. (4) from the comover formation time τ_0 to infinity

$$-\frac{\Delta N_\psi}{N_\psi} = \tilde{\sigma}_\psi F(\xi) \simeq \tilde{\sigma}_\psi F\left(\frac{\langle v_{\psi c} \rangle \tau_0}{2R}\right) - \frac{\tilde{\sigma}_\psi \delta}{2} \frac{v_\psi^2}{\langle v_{\psi c}^2 \rangle} \cos(2\phi), \quad (9)$$

where we have introduced the function ($C = 0.557\dots$)

$$F(\xi) \equiv \int_0^\infty \frac{e^{-x'^2} dx'}{\xi + x'} = \begin{cases} \log(\frac{1}{\xi}) - \frac{C}{2}, & \xi \ll 1 \\ \sqrt{\pi}/2\xi, & \xi \gg 1 \end{cases}. \quad (10)$$

With typical relative velocities and formation times we find $\langle v_{\psi c} \rangle \tau_0 \ll R$ except for the very peripheral collisions. From Eq. (8) thus $\xi \ll 1$ for central and semi-central collisions.

The result of Eq. (9) for comover absorption gives the average suppression (see Fig. 2) as well as a characteristic oscillation with the azimuthal angle between reaction plane and the transverse momentum of the charmonia (see also Fig. 3). It is important to observe that the average and the amplitude of the absorption probes different space-times of the collision and therefore different physics: *The average absorption occurs at early times* because densities decrease inversely with proper time which leads to the logarithmic dependence of the initial time τ_0 as is also found in the comover model of [5]. Contrarily, *the amplitude of the oscillation is more sensitive to later times* of order $\tau \simeq 2R/v_\psi$ due to the extra factor $(\tau - \tau_0)^2$ that appears in (4) when expanding for small deformations as in Eq. (9). The physics behind this late time effect on the amplitude, is that the particle has to travel a distance $\sim R$ before the deformation of the source leads to more or less absorption. Likewise the amplitudes decrease with the transverse velocity as v_ψ^2 because the slow charmonia do not have the time travel the distance R before the comovers have expanded on a time scale R/v_c .

For more central collisions the free streaming assumption breaks down as interactions between comovers drive the system towards thermal equilibrium and hydrodynamic expansion. Also the absorption is a significant fraction and the linear expansion of Eq. (9) breaks down. For simplicity, we shall assume that the free streaming result of Eq. (4) is approximately valid for the comovers in central collisions as well. The heavy charmonia do not thermalize but rather break up when interacting and therefore the distribution function for the remaining charmonia is free streaming to a good approximation. By taking proper time derivative of Eq. (4) and treat N_ψ as a decreasing function with time, we obtain by integrating over time that

$$\frac{N_\psi}{N_\psi(\tau_0)} \simeq e^{-\tilde{\sigma}_\psi F(l)} \quad (11)$$

$$\simeq \left(\frac{\langle v_{\psi c} \rangle \tau_0}{e^{-C/2} 2R} \right)^{\tilde{\sigma}_\psi} \left(1 + \frac{\tilde{\sigma}_\psi \delta}{2} \frac{v_\psi^2}{\langle v_{\psi c}^2 \rangle} \cos(2\phi) \right), \quad (12)$$

where the latter expansion is valid for central and semi-central collisions where $\langle v_{\psi c} \rangle \tau_0 / R$ and δ are small. $N_\psi(\tau_0)$ is the number of J/Ψ 's at time τ_0 where comover absorption sets in.

In the wounded nucleon model also the transverse energy E_T scales with the transverse area, i.e., $R_x R_y \simeq R^2 \propto E_T$. Consequently, the J/Ψ suppression decreases with centrality as a power law, $J/\Psi \propto E_T^{-\tilde{\sigma}/2}$. It differs from the exponential fall-off of the comover model of [5] that results from assuming that number densities and thus effective opacities scales linearly with E_T .

The transverse momentum, rapidity and centrality dependence of the amplitude in Eq. (12) differs from the average suppression. The amplitude is increase proportionally to dN/dy and p_\perp^2 but decreases as δ almost linearly with centrality, E_T . The relative amplitudes for $J/\Psi, \Psi', \chi$, etc. are proportional to the absorption cross section and should therefore scale with these when corrected for feeddown whereas the DY background should not oscillate.

We note that the prefactor to $\cos \phi$ is exactly the elliptic flow parameter ($2v_2$) if the absorption cross section is replaced by the momentum transport cross section, σ_{tr} [11]. The elliptic flow of pions and proton $v_2 \sim 0.1$ for pions and protons could be described with $\sigma_{tr} \simeq 10$ mb. Therefore, the magnitude of the charmonium absorption amplitude is approximately $\sim 2v_2 \sigma_{\psi c} / \sigma_{tr} \simeq 5\%$ depending on rapidity and transverse momentum.

III. GLAUBER ABSORPTION

Glauber absorption of charmonium on nucleons is believed to be more important at SPS energies than comover absorption. The dissociation cross sections on nucleons and secondaries depend on various model assumptions. Typically, for nuclear absorption one takes $\sigma_{\psi N} \simeq 3\text{--}5$ mb and assumes that comovers scatter with cross sections varying from $\sigma_{\psi c} \simeq 1\text{--}5$ mb [6,5,7]. The relative amount of Glauber versus comover absorption is, however, unresolved at present since it is also possible to describe the charmonium by Glauber absorption—at least for p+A and S+U reactions—taking $\sigma_{\psi N} \simeq 7$ mb [4]. Furthermore, it has been pointed out that feed-down effects from Ψ' and χ -decays into J/Ψ [8] or formation times [12,7] can play a major role.

As we shall concentrate on azimuthal asymmetries, we choose the standard model for Glauber absorption

$$G_{AB}(b) = \mathcal{N} \int d^3r d^3r' \rho_A(r) \rho_B(r') \delta^2(\mathbf{b} - \mathbf{r}_\perp + \mathbf{r}'_\perp) \times \exp(-L_A(r) - L_B(r')), \quad (13)$$

where $\rho_{A,B}$ are the nuclear densities, $L_A(r) = \sigma_{\psi N} \int_z^\infty dz_A \rho_A(\mathbf{r}_\perp, z_A)$, and analogously for $L_B(r')$. The normalization constant \mathcal{N} is chosen such that $G_{AB}(b) = 1$ when $L_A = L_B = 0$. For simplicity we use the Glauber absorption of J/Ψ with $\sigma_{J/\Psi N} = 3.6$ mb as in [8] and no formation time.

The straight line geometry implied by the Glauber model for absorption does not contain any azimuthal asymmetry, i.e., it is independent of ϕ . In the NA50 experiment the J/Ψ 's are collected at pseudorapidities $\eta = 2.8\text{--}4$ corresponding to angles of 2-7 degrees with respect to the beam axis. The J/Ψ 's thus traverses a transverse distance $r_\perp \simeq R v_\perp \cosh(\eta) \simeq 0.2\text{--}0.9$ fm inside the nuclei and their absorption might be affected by the density distribution variation transversely. However, the net absorption from opposite direction depends on the curvature of and not the gradient of the transverse density distribution. Therefore, the resulting azimuthal dependence of Glauber absorption is $\sim (r_\perp/R_x)^2 - (r_\perp/R_y)^2 \sim \delta(r_\perp/\bar{R})^2$. It amounts to a few percent at midrapidity but is negligible at the forward rapidities.

Momentum broadening affects the initial charmonium production rates and is another possible mechanism which could introduce azimuthally dependence in Glauber absorption. Momentum broadening has been found in pA and BA collision at relativistic energies and depends on the number of NN collisions and therefore also the nuclear thickness function. The momentum broadening could be sensitive to the varying density profile depending on the range of the interaction, r_i . As above the resulting azimuthal dependence of Glauber absorption is $\sim (r_i/R_x)^2 - (r_i/R_y)^2$. Furthermore, it has to be multiplied with the relative momentum broadening. With $r_i \sim 1$ fm we estimate that this effect is also small. Since DY pairs should be affected by momentum broadening of the cascading nucleons like Glauber absorption but not by comover absorption, it is possible to discriminate between the azimuthal dependence of Glauber and comover absorption by measuring the amplitude for Drell-Yan (DY) production.

These rough estimates clearly deserve more study in detailed microscopic models which, however, is outside the scope of this work. We emphasize that the time scales and distances involved for the initial Glauber scatterings are very short. Causality limits particles to probe transverse distance scales shorter than $\sim R_z/\gamma$, where γ is the Lorentz contraction factor. Such short distances are to be compared to the transverse radii, $R_{x,y}$, over which densities vary azimuthally.

Predictions for RHIC and LHC energies depend on the charmonium absorption cross section at these energies. If formation times are $\tau_\psi \gtrsim R/\gamma$, the Glauber absorption might disappear or be enhanced at higher energies due to time dilation [12] and different production mechanisms as e.g. suggested by the color-singlet or the color-octet model. However, pA Fermilab data on J/Ψ

production [13] indicates that the absorption cross section does not change going from 200 to 800 GeV lab energy. For the estimates presented below we therefore assume that the Glauber absorption is unchanged going from SPS to RHIC and LHC energies. Furthermore, the minor azimuthal dependence of Glauber absorption will be ignored.

IV. ESTIMATES FOR SPS, RHIC AND LHC

First we estimate the parameters in play. The unknown ones are the comover absorption cross section, $\sigma_{\psi c}$, and the formation time τ_0 . The other parameters and their dependence on impact parameter can be estimated from experiments and results in an almost constant opacity as explained above. We give an estimate for central $Pb + Pb$ collisions at SPS energies. Here, the rms radius is $R^2 \simeq 10 \text{ fm}^2$, and the total rapidity density is $dN^{tot}/dy \simeq 500$. One can assume [5] that only heavy resonances as ρ, ω, ϕ , etc. have sufficient energy to destroy the charmonia and take $dN_c/dy \simeq 0.5 dN^{tot}/dy$. The average relative velocity for charmonia with transverse momentum $\sim 1 \text{ GeV}/c$ is $v_{\psi c} \simeq 0.6c$. A comover absorption cross section of order $\sigma_{\psi c} = (2/3)\sigma_{\psi N} \simeq 2.4 \text{ mb}$ is typically assumed, and so we obtain the opacity $\tilde{\sigma} \simeq 0.3$ for central and semi-central collisions. Its dependence on centrality for peripheral collisions is calculated in the wounded nucleon model [11].

At RHIC and LHC energies the rapidity density is expected to increase with collision energy and we shall simply assume that they double at RHIC energies and triple at LHC energies. Consequently, the opacity is $\tilde{\sigma} = 0.3, 0.6$, and 0.9 at SPS, RHIC and LHC energies respectively. In Fig. 2. we show the corresponding comover suppression of the J/Ψ from Eq. (11-12) assuming $\tau_0 = 1 \text{ fm}/c$ and taking the same standard Glauber absorption from Eq. (13) with $\sigma_{\Psi N} = 3.6 \text{ mb}$ at all three energies.

The modulation of the J/Ψ -suppression with angle between p_\perp and reaction plane is shown in Fig. 3 for five centralities or E_T corresponding to impact parameter $b/R \simeq 2, 1.5, 1, 0.5, 0$. For a prediction at RHIC we take the same Glauber absorption as in Fig. (2) as well as the SPS values for $v_\psi \simeq 0.3c$ and $v_{\psi c} \simeq 0.6c$. However, $\tilde{\sigma} \simeq 0.6$ is employed for RHIC energies due to the larger rapidity densities. The relative amplitude is given by Eq. (12) and decreases with centrality as the deformation. For near-central collisions the source expands significantly and the deformation may be smaller than that at initial overlap, $\delta \simeq b/2R$. The magnitude of the amplitude is up to $\pm 7\%$ for semi-peripheral events. As the relative amplitude scales with the rapidity density, it is smaller by a factor of two at SPS energies but larger at LHC energies.

The relative amplitudes should be measurable by techniques similar to those used for extracting elliptic flow [9]. By taking the ratio of the amplitude to the average J/Ψ

or using a minimum bias analysis, the largest statistical uncertainty (the DY background) is removed. The NA50 minimum bias data has a relative error bar of 1-2%, i.e., an order of magnitude less than the variation in the J/Ψ absorption, $[N_\psi(\phi = 0) - N_\psi(\phi = \pi/2)]/\bar{N}_\psi$, which is twice the amplitude in Eq. (12).

It would also be most interesting to measure and compare the amplitude for the various charmonium states $J/\Psi, \Psi', \chi$ as well as for the DY background. The Ψ' is expected to have a larger dissociation cross section and the amplitude should be correspondingly larger. The amplitude for the DY background should vanish as discussed in the previous section.

V. EFFECTS OF A PHASE TRANSITION

The anomalous J/Ψ suppression measured by NA50 is possible due to the formation of a plasma state leading to color screening of $c\bar{c}$ pairs [2,3]. As the plasma is created at high energy densities present at early times it would increase the average suppression. However, the amplitude would be less affected since it is caused by late time absorption. We can mimic this situation by employing a larger absorption cross section at early times than at late times or in terms of Eq. (12) a larger $\tilde{\sigma}$ in the average power law suppression than in the prefactor to the amplitude. Both quantities can be measured as function of centrality and it would be most interesting to follow their behavior for the J/Ψ and Ψ' suppression as well as the subthreshold enhancement - in particular in the regions of anomalous J/Ψ and Ψ' and suppression.

If the charmonium absorption cross sections are strongly energy dependent [4], the average cross section $\langle v_{\psi c} \sigma_{\psi c} \rangle$ may also be larger at earlier times since the relative energies are larger here. In the above calculations we ignored relative longitudinal velocities by assuming the $\delta(y - \eta)$ factor in the distribution. This approximation breaks down at early times and one should therefore take an effective cross section at larger collision energy in Eq. (12) at early times. However, whereas the energy dependent cross sections should lead to a smooth variation of the average J/Ψ -suppression as well as its amplitude, the plasma leads to an anomalous and sudden suppression at a certain centrality or E_T [3,4].

VI. SUMMARY

In summary, we have investigated suppression of charmonia in non-central collisions and find a characteristic oscillation with azimuthal angle between transverse momentum and reaction plane due to comover absorption. Glauber absorption was estimated to contribute less to the amplitude because causality strongly constrains the transverse distances probed and the resulting azimuthal dependence. Therefore, the azimuthal variation may be

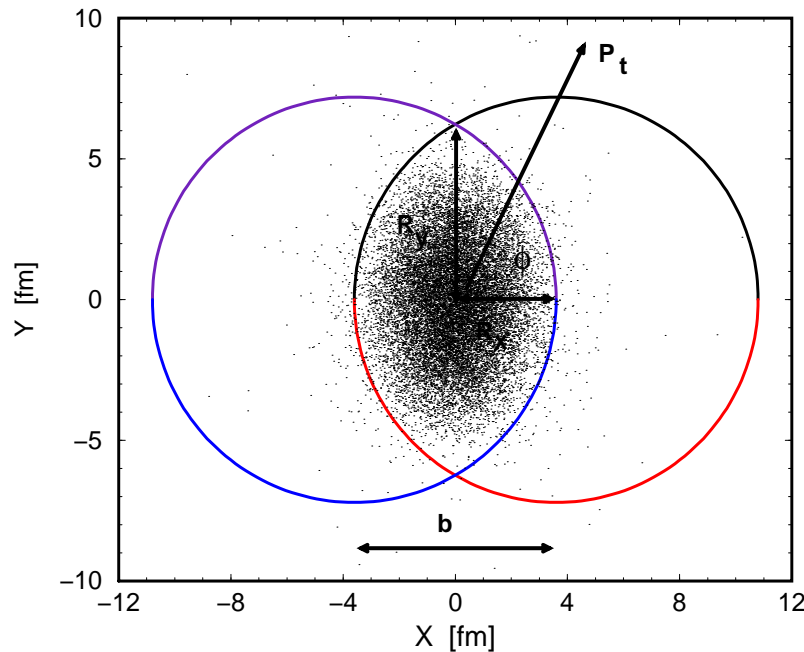
exploited to gain more information on the suppression mechanisms.

Estimates for comover absorption predicts an azimuthal variation of order 5-20% in the number of J/Ψ depending on centrality, size and energy of the colliding nuclei. Such an oscillation should be detectable (if the reaction plane can be determined event-by-event) as it is not sensitive to the statistical uncertainty of the DY background. In comparison, the current minimum bias data of NA50 has error bars of 1-2%.

The amplitude has a strong dependence on rapidity and transverse momentum of the charmonia and on centrality that is different from the average suppression. The amplitude is proportional to dN/dy and p_{\perp}^2 and decreases almost linearly with centrality E_T . The relative amplitudes for J/Ψ , ψ' and χ are proportional to the absorption cross section and should therefore scale with these when corrected for feeddown. The DY background should, however, not oscillate.

The average absorption and its amplitude are more sensitive to early and later times respectively. This distinction may further be exploited to obtain additional information on the absorption mechanism and whether an anomalous suppression is due to a phase transition.

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□

FIG. 1. Reaction plane of a semi-central $Pb + Pb$ collision with impact parameter $b = R_{Pb} \simeq 8\text{fm}$. The overlap zone is deformed with $R_x \leq R_y$. The reaction plane (x, z) is rotated by the angle ϕ with respect to the (outward) transverse particle momentum p_\perp . The scatter plot shows charmonium dissociation points in a microscopic cascade simulation [14] at SPS energies.

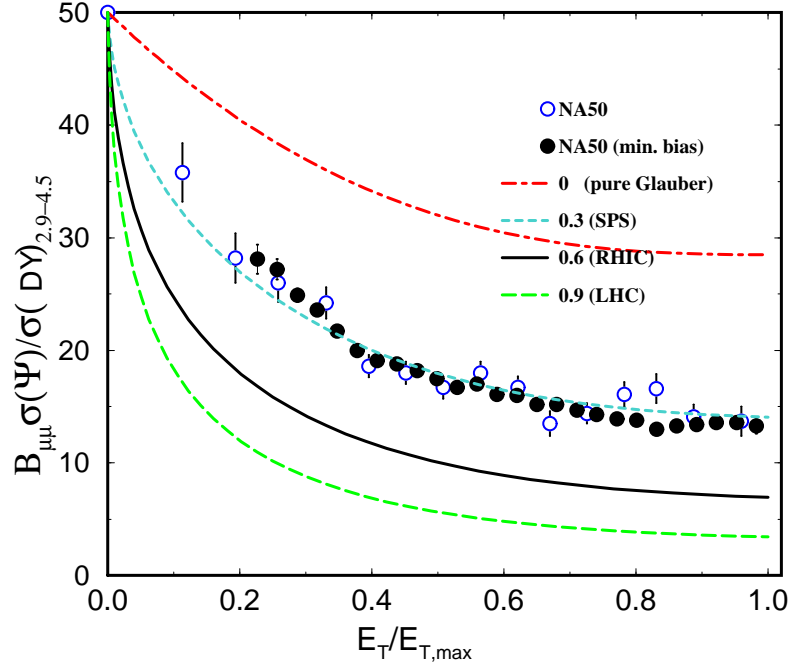


FIG. 2. Comover and Glauber suppression of J/Ψ , Eqs. (11-13), shown by curves as function of transverse energy E_T . The opacities are: $\bar{\sigma} = 0.0, 0.3, 0.6, 0.9$ corresponding approximately to pure Glauber absorption, SPS, RHIC and LHC energies (see text for details). Also shown is NA50 data [1] normalized to DY and minimum bias (open and filled circles respectively).

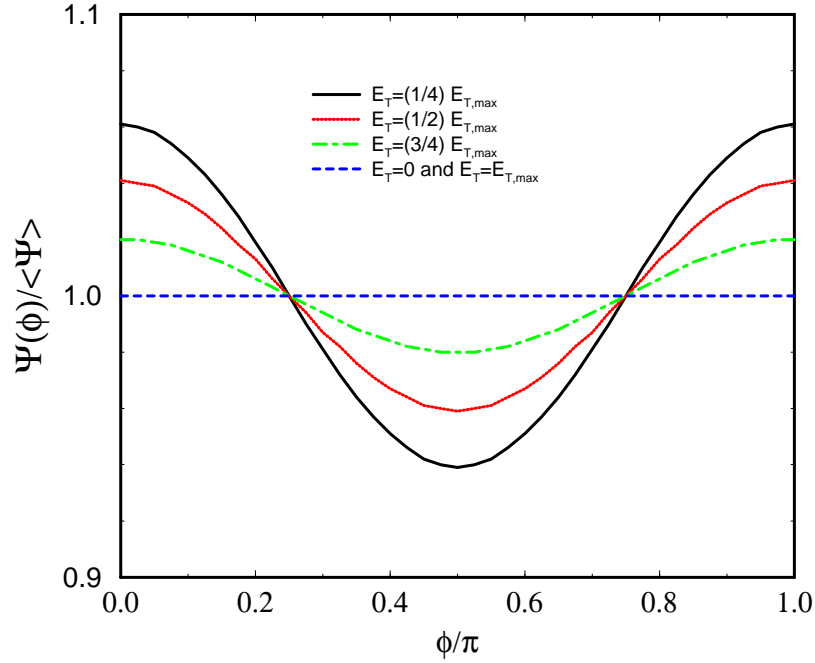


FIG. 3. J/Ψ suppression as function of azimuthal angle ϕ normalized to its average for various centralities from Eq. (12). The RHIC parameters $\bar{\sigma} = 0.6$ are employed (see text).